



Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at <http://about.jstor.org/participate-jstor/individuals/early-journal-content>.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

AN ATTEMPT TO FRAME A WORKING HYPOTHESIS OF THE CAUSE OF GLACIAL PERIODS ON AN ATMOSPHERIC BASIS ¹

THERE are hypotheses and working hypotheses. The suggestion that the last glacial period was caused by the passage of the solar system through a cold region of space may be styled a hypothesis, but scarcely a working hypothesis in the geological sense, for it does not form the groundwork or incentive of geological inquiry. An astronomer might be moved to hunt for the cold spot, but it has no inspiration for the geologist. General suggestions of a possible cause do not reach the dignity of working hypotheses until they are given concrete form, are fitted in detail to the specific phenomena, and are made the agents of calling into play effective lines of research. The construction of a concrete working hypothesis suited to stimulate and guide investigation in a wholesome manner, and to take its place in competition with other hypotheses of like working potentialities, thereby inducing a more searching scrutiny of the phenomena and a more varied application of interpretations, represents the higher limit of present reasonable aspiration. It is much too ambitious to hope for a demonstrative solution of the origin of the earth's glacial periods by first intention in the present state of knowledge.

The hypothesis here offered is not worked out into satisfactory detail at all points, but it is hoped that it is sufficiently matured to justify a preliminary statement. In forming it, which has been the work of several years, I have found, or seemed to find, the phenomena of past glaciation intimately associated with a long chain of other phenomena to which at

¹ A brief statement of the salient features of this hypothesis was given in a paper entitled *A Group of Hypotheses Bearing on Climatic Changes*, *JOUR. GEOL.*, Vol. V, pp. 653-683, Oct.-Nov. 1897. For earlier history see footnotes on pp. 654 and 681 of that paper.

first they appeared to have no relationship. This chain led on and on until it became connected with many of the most fundamental problems of geology. When once an inquiry into the history of the atmosphere and its possible functions in the past was raised, there seemed no resting place until the origin of the atmosphere — and with it the origin of the earth — was reached. The inquiry raised profound skepticism regarding some of the most firmly accepted doctrines of the original state of the earth, its internal constitution, and the great dynamic forces that have controlled the larger phases of its history. A series of new, or partially new, hypotheses relative to these fundamental phenomena seemed to be necessary to fill out the group of alternative theories requisite to cover the ground of legitimate doubt based on specific reasons for doubt. In other papers I have given a partial expression to the hypotheses framed to cover these points.¹ The exposition of these has not in all cases been sufficiently ample to give them good working form, but has perhaps been sufficient to show their general relationship to an atmospheric hypothesis of glaciation.

The hypothesis here offered is confessedly connected in my own mind with these ulterior and more fundamental hypotheses, but it does not seem to me that it is necessarily so connected. To be sure, if it is assumed, following a prevalent custom of the past, that the original atmosphere was a vast gaseous envelope embracing essentially all the carbonic acid that is now locked up in limestone and other carbonates, and all that is represented by coal and other carbonaceous matter, and that the atmospheric history has been essentially a progressive depletion of this original supply, I do not see how the proposed hypothesis can be entertained, at least for the earlier glaciations. But if it be

¹ A Group of Hypotheses Bearing on Climatic Changes, *JOUR. GEOL.*, Vol. V, No. 7, 1897. The Ulterior Basis of Time Divisions and the Classification of Geologic History, *ibid.*, Vol. VI, No. 5, 1898. A Systematic Source of Evolution of Provincial Faunas, *ibid.*, No. 6, 1898. The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *ibid.*, Lord Kelvin's Address on the Age of the Earth as an Abode Fitted for Life, *Science*, N. S., Vol. IX, No. 235, pp. 889-901, June 30, 1899, and Vol. X, No. 236, pp. 11-18, July 7, 1899.

assumed that as early as Paleozoic times the atmosphere had some such constitution as it possessed in later geological times, and that its history has been a contest between the agencies of atmospheric supply and the agencies of atmospheric depletion, and that the constitution of the atmosphere at any time has been dependent upon the relative rates of supply and depletion, then the hypothesis may be entertained quite independently of all views of the origin of the earth and the atmosphere and of internal dynamics.

Previons advocacy of an atmospheric hypothesis.—The general doctrine that the glacial periods may have been due to a change in the atmospheric content of carbon dioxide is not new. It was urged by Tyndall a half century ago and has been urged by others since. Recently it has been very effectively advocated by Dr. Arrhenius,¹ who has taken a great step in advance of his predecessors in reducing his conclusions to definite quantitative terms deduced from observational data.² The great labor involved in this and the specific results springing from it place his contribution on a much higher plane than the general suggestions of those who had preceded him. Valuable as these general suggestions were, they must still be regarded as falling much short of working hypotheses, since no attempt was made to show that changes in the content of carbon dioxide of such a degree as would be compatible with the continuity of life and with other limiting geological conditions were quantitatively competent to produce the effects assigned them; nor were modes of inquiry into this essential matter suggested. It is one thing to point out a theoretical *causa vera*, and quite another thing to give good reasons for believing that it is quantitatively sufficient, and to open lines of inquiry for demonstrating that it is so. This Dr. Arrhenius has done and apparently with great success. While his results are doubtless to be regarded as subject to modification when more full and exact data are at hand,

¹ On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, by SVANTE ARRHENIUS, Phil. Mag., April 1896, pp. 237-276.

² See review of his paper in this number of the JOURNAL, p. 623.

it is apparent upon inspection that they can be very largely modified and still fall within the limits of the conditions of the case. This will perhaps appear more evident in the course of the subsequent discussion. In so far as the deductions of Arrhenius and the accompanying views of Professor Högbom¹ fail to definitely postulate operative geological agencies competent to produce the requisite variations in the constitution of the atmosphere, and to give reasons for believing that such agencies were in operation at the times requisite to produce the effects assigned them, they fall short of furnishing an ample working hypothesis from the geologist's point of view. This, of course, is the function of the geologist rather than the chemist and the physicist. Professor Högbom has made a valuable contribution to the general doctrine of consumption and supply.

To form a good working hypothesis in a geological sense, it is furthermore necessary to assign subsidiary agencies working in an oscillatory manner correspondent with the oscillations of glaciation now so well authenticated by observation.

Specific requisites of a working hypothesis.—It is obvious that it is necessary at the outset to assign agencies capable of reducing the amount of the carbon dioxide of the atmosphere at the time of the glaciations. If there were no other glaciation than that of the Pleistocene period, and if there were no kindred phenomena needing to be elucidated at the same time, it might be sufficient to point to the well-known abstraction of carbon dioxide from the atmosphere in the formation of limestones and carbonaceous deposits, and there rest the case, with the implication that further production of limestones and carbonaceous deposits would insure further glaciation, and that the permanent and final winter of the earth is at hand. A very slight computation of the rate at which carbon dioxide is now consumed is sufficient to show that an effective depletion of the atmosphere is near at hand unless there be sources of supply approximately equal to the depletion. But recent depletion touches only the

¹ SVENSK KEMISK TEDSKRIFT, Bd. VI, p. 169 (1894). Quoted in Dr. Arrhenius's paper, p. 269.

easier part of the problem. Whatever may be thought of the supposed signs of cold periods at other early periods, the evidences of glaciation in India, Australia and South Africa near the close of the Paleozoic era are so abundant, so specific, and so well attested, that they cannot be ignored, and any hypothesis that assumes to account for glacial periods must take serious cognizance of these and must meet the strenuous issues that spring from their early age and from the mildness of the periods following them. It seems to the writer almost equally necessary to take cognizance of the salt and gypsum deposits of various periods, which imply degrees of aridity in relatively high latitudes scarcely equaled at the present day. If the atmospheric line is followed, it seems necessary to postulate a reduction of carbon dioxide near the close of the Paleozoic era—to say nothing of other early times—so effectual as to produce glaciation between 20° and 35° latitude on both sides of the equator, a glaciation the deposits of which aggregate a greater thickness than those of Pleistocene times, and whose oscillations, marked by thick accumulations of coal, were even more remarkable than those of the Pleistocene glaciation. If a depletion of the carbon dioxide of the atmosphere sufficient to produce this glaciation at this relatively early stage in geological history is postulated, it is necessary to assign agencies for the reënrichment of the atmosphere in carbon dioxide to account for the mild climates in high latitudes in Jurassic, Cretaceous, and Tertiary times. In short, it is necessary to assign competent operative geological agencies which shall produce effective depletion alternating with effective reënrichment of the atmosphere from an early period in its history down to the present time. If the salt and gypsum deposits, and the prevailing red beds, with arkose elements, be regarded as the products of exceptional aridity, and if this be assigned to the localization and intensification of heat and moisture due to the removal of carbon dioxide, as subsequently set forth, it is necessary to multiply the oscillations from enrichment to depletion very notably, and to extend the alternating action at least as far back as the close of the Silurian period

when the great saline deposits of New York, Ontario, Ohio, Michigan and adjacent regions were laid down.

Primary assumptions.—(1) It is therefore assumed as the working basis of the hypothesis that the carbon dioxide of the Paleozoic atmosphere was at certain stages not essentially greater than it is today, that at the specific epochs of great saliferous deposition and of glaciation it was reduced to a quantity notably less than the present content, while at other and intervening stages its amount exceeded the present content by some multiple—these latter periods being those in which the wide extension of marine epicontinental life took place. For myself, I am disposed to extend the assumption of a measurably limited atmosphere back to the very beginning. To this I am led in part by the conviction that the gravitation of the earth is incompetent to hold an atmosphere very greatly beyond the amount so assumed, and by the much more speculative consideration that the earth may have grown up by slow accretion rather than rapid concentration, and that hence the early development of the atmosphere was controlled by limitations much like those that have affected it in its later history. But, as already remarked, this assumption is not regarded as vital to the hypothesis. (2) Wrapped up in the foregoing postulate is an assumption of the essential correctness of the doctrine of Arrhenius that variations of the atmospheric carbon dioxide falling within limits compatible with life and with other geological phenomena, are competent to effectively change the thermal state of the atmosphere. This needs further statement.

The functions of carbon dioxide.—By the investigations of Tyndall,¹ Lecher and Pretner,² Keller,³ Röntgen,⁴ and Arrhenius,⁵ it

¹ Heat as a Mode of Motion, 6th ed., pp. 345–349, 1892. Contrib. to Mol. Physics, pp. 38. 117, 421, 1888.

² Sitzungsberichte des Akad. der Wissenschaften d. Wien (2). Vol. LXXXII, p. 851 (2), Vol. LXXXVI, p. 52.

³ Am. Jour. Sci. (3), Vol. XXVIII, p. 190.

⁴ Poggendorfs Annalen (2), Vol. XXIII, p. 1259.

⁵ Phil. Mag., Vol. XLI, pp. 237–279.

A brief statement of the conclusions of these authors is given in the article of Mr. Tolman in this number, p. 586. See also his review of Dr. Arrhenius, p. 623.

has been shown that the carbon dioxide and water vapor of the atmosphere have remarkable power of absorbing and temporarily retaining heat rays, while the oxygen, nitrogen, and argon of the atmosphere possess this power in a feeble degree only. It follows that the effect of the carbon dioxide and water vapor is to blanket the earth with a thermally absorbent envelope. Their absence would leave the surface of the earth essentially exposed to the free impact and free radiation of the solar rays, measurably, though of course not entirely, as if the earth were devoid of atmosphere. A reduction or an increase in these constituents would produce corresponding partial effects. The general results assignable to a greatly increased or a greatly reduced quantity of atmospheric carbon dioxide and water may be summarized as follows:¹

a. An increase, by causing a larger absorption of the sun's radiant energy, raises the average temperature, while a reduction lowers it. The estimate of Dr. Arrhenius, based upon an elaborate mathematical discussion of the observations of Professor Langley, is that an increase of the carbon dioxide to the amount of two or three times the present content would elevate the average temperature 8° or 9° C. and would bring on a mild climate analogous to that which prevailed in the Middle Tertiary age.² On the other hand, a reduction of the quantity of carbon dioxide in the atmosphere to an amount ranging from 55 to 62 per cent. of the present content, would reduce the average temperature 4° or 5° C., which would bring on a glaciation comparable to that of the Pleistocene period.

The amount of moisture in the atmosphere, other things being equal, is directly dependent upon the temperature, and the temperature in turn is dependent upon the amount of moisture in the atmosphere. This reciprocal dependence renders the aqueous

¹ The action has two phases that in an exhaustive exposition would need separate statement, (1) the absorption of solar rays before they reach the earth, and (2) the absorption of the rays radiated by the earth. The latter have longer wave-lengths on the average and are relatively much more affected by the constitution of the atmosphere.

² Dr. Arrhenius, *loc. cit.*

vapor a vacillating factor subject to the control of any other agency which increases or decreases the atmospheric temperature. Whenever therefore an increase of carbon dioxide raises the temperature, it increases the quantity of water vapor and this by its thermal absorption further increases the temperature and calls forth more vapor and this action and reaction continue in diminishing force until an equilibrium is established. A decrease in carbon dioxide decreases the temperature and thus lessens the water vapor, and this further lowers the temperature and inaugurates a reversed series of actions and reactions. Fluctuation in the quantity of carbon dioxide therefore is attended not simply by its own individual effects, but by these auxiliary effects also. The carbon dioxide becomes therefore the determinative factor, and the question of the thermal absorption of the atmosphere may be discussed for convenience as though it were solely dependent upon the fluctuations in the content of this constituent, although this will not be strictly exhaustive.

b. A second effect of increase and decrease in the amount of atmospheric carbon dioxide is the equalization, on the one hand, of surface temperatures, or their differentiation on the other. The temperature of the surface of the earth varies with latitude, altitude, the distribution of land and water, day and night, the seasons, and some other elements that may here be neglected. It is postulated that an increase in the thermal absorption of the atmosphere *equalizes* the temperature, and tends to eliminate the variations attendant on these contingencies. Conversely, a reduction of thermal atmospheric absorption tends to *intensify* all of these variations. A secondary effect of intensification of differences of temperature is an increase of atmospheric movements in the effort to restore equilibrium. Increased atmospheric movements, which are necessarily convectional, carry the warmer air to the surface of the atmosphere, and facilitate the discharge of the heat and thus intensify the primary effect. In the case of a naked earth, the radiant energy of the sun falling directly upon the tropical belt is concentrated in space, and subject to the minimum reflection; in high latitudes, the rays

are spread over greater space, and are subject to greater relative reflection because of the low angle of incidence. In the case of an earth swathed in a thermally absorptive mantle, the direct equatorial ray is absorbed in traversing the atmosphere to a less extent than the ray of higher latitudes because it penetrates a less depth of atmosphere, while the amount of reflection from the atmosphere is small in both cases, so far as the transparent elements are concerned. In so far therefore as the temperature effects are dependent upon the absorption of the incoming rays, the greater depth of atmosphere penetrated in the higher latitudes makes important compensation for obliquity of incidence.

In the case of a naked earth, or an earth clothed with a non-absorptive atmosphere, the solar rays which are tangential to the polar regions have no heating influence upon the earth, while in the case of an earth clothed with an absorbent atmosphere, similar rays are partially absorbed, and serve to warm the earth. In the polar regions, therefore there is a very radical difference between the effects of an absorbent and a non-absorbent atmosphere. The same holds true of the heating effects of the morning and evening sun. With a non-absorbent atmosphere, the tangential morning and evening rays pass through and are lost; in a thermally absorbent atmosphere, they are effectually retained.

In so far as the incoming rays are absorbed in the atmosphere their immediate effects are chiefly felt in its upper strata and their influence upon the surface of the earth is lessened. This is due to the fact that the upper regions are penetrated by rays of all the various wave-lengths that emanate from the sun, while the lower portions are penetrated only by such rays as are left after the selective absorption of the upper atmosphere. The degree of this absorption of the rays of long wave-lengths is such that comparatively little further absorption takes place in the basal portion of the atmosphere, according to the interpretations of Arrhenius. One effect of increasing the absorptive capacity of the upper air by increasing the amount of carbonic acid is an increase in the elevation of the strata chiefly heated by the

incoming rays and the consequent reduction of the thermal gradient of a vertical column of the atmosphere. As a result there is less effective tendency to convection and less discharge of heat from the atmosphere.

In high latitudes, besides this effect, it is also to be noted that with an increase of the absorptive capacity of the upper atmosphere, rays that previously passed through the higher strata with little absorption are arrested and contribute heat to the upper air. The same is true of morning and evening rays at high elevations.

In the case of the outgoing rays, which are absorbed in much larger proportions than the incoming rays because they are more largely long-wave rays, the tables of Arrhenius¹ show that the absorption is augmented by increase of carbonic acid in greater proportions in high latitudes than in low; for example, the increase of temperature for three times the present content of carbonic acid is 21.5 per cent. greater between 60° and 70° N. latitude than at the equator. The maximum thermal effects also lie in higher latitudes for the summer months than for the winter months. On the other hand, when the carbonic acid is reduced to 0.67 of the present content, the maximum winter variation is felt between 30° and 40° N. latitude. If the carbonic acid be further reduced, the maximum variation found by extrapolation falls at and below 30°, the latitude of the Carboniferous glaciation. It is not intended, however, to imply that this would be sufficient in itself to produce that glaciation.

An atmosphere having a relatively large percentage of carbon dioxide and water, *i. e.*, an absorptive atmosphere, has a higher heat content than a non-absorptive one, and its circulation in latitude more effectually equalizes the temperature with the same degree of movement.

Similar considerations are applicable to the effects of land and water areas. In so far as the atmosphere absorbs the incoming rays in passing through it, the amount that reaches the surface of the earth is reduced. To this extent the possibility of

¹ Loc. cit., p. 266.

differential effects between the sea and land is lessened. On the other hand, in the absence of absorptive and diffusive effects, the tropical rays fall with full intensity upon the surface. On the land they promptly heat the immediate surface, and the heat is as promptly radiated away. On the sea, neglecting reflection, they penetrate deeply into the water until they are absorbed. The upper layer of the sea is therefore heated to a notable depth, and radiates its heat away with relative slowness. The result is an intensification of the differences in average temperature of the land and the sea. This action is quite familiar, but perhaps not the point here urged—that this difference is dependent on the atmospheric effects upon the incoming as well as outgoing rays. If the atmosphere were so far robbed of its absorbent factors, carbon dioxide and water, as to give great intensity to this differential effect, the result might be an average temperature of the land below the freezing point, while that of the sea might be relatively warm. It seems clear that at some point short of an absolute thermal transparency a stage would be reached where the average temperature of the land would sink below zero, while yet the sea, barring convection in latitude, would retain a comparatively mild temperature. There would then apparently arise, even in low latitudes, the conditions of glaciation.

Without following out these lines into greater detail, the more pertinent deductions may be summed up in the following propositions: A reduction of the thermal absorption of the atmosphere would intensify the differences of temperatures between (1) the basal and the upper portions of the atmosphere; (2) low and high latitudes; (3) land and sea; (4) night and day; and (5) the seasons. In short, it would intensify temperature differences generally, and would lead to (1) greater local heat, as well as greater local cold; (2) to greater local dryness, as well as greater local moisture; (3) to more intense movements of the atmosphere in the endeavor to maintain equilibrium; and (4) to lower average temperature. The effect of reducing the absorbent factors is the intensification of differences.

On the other hand, an increase in the absorptive factors renders ineffectual, in a corresponding degree, the variations of altitude, of latitude, of land and sea, of day and night, and of the seasons, and conduces to an equable and mild temperature, to gentle and yet thermally effective circulation, and to higher average temperature. As Arrhenius has remarked, "The geographical, annual, and diurnal changes of temperature would be partly smoothed away if the quantity of carbonic acid was augmented. The reverse would be the case (at least to a latitude of 50° from the equator) if the carbonic acid diminished in amount."¹

AGENCIES OF DEPLETION AND ENRICHMENT

It now becomes necessary to assign agencies capable of removing carbon dioxide from the atmosphere at a rate sufficiently above the normal rate of supply, at certain times, to produce glaciation; and on the other hand, capable of restoring it to the atmosphere at certain other times in sufficient amounts to produce mild climates.

These agencies on both sides belong to two classes, the permanent and the temporary, and the distinction has practical importance.

Sources of permanent loss.—Permanent depletion results from the consumption of carbon dioxide in the transformation of the silicates of the original earth, and of volcanic products into the carbonates of the secondary strata. It is fairly safe to assume that the original earth's surface was composed of material of the general class represented by the igneous rocks and the basement complex. These, it is needless to say, consist largely of silicates with which are associated certain quantities of certain gases to be considered more fully hereafter. These silicates, where exposed to the weathering action of the atmosphere, become decomposed and take the form of carbonates (with less quantities of sulphates, phosphates, etc.) and of residual silicates and oxides (kaolin, quartz, ferric oxides, etc.). Neglecting the minor transformations which do not concern us here, the operation may be

¹ Loc. cit., p. 268.

characterized as carbonation, and consists essentially of the substitution of carbonic acid for the silicic acids. The carbonic acid is derived, in the main, from the atmosphere. In their soluble condition, the carbonates so formed are largely bicarbonates. This is the only form in which calcium carbonate is appreciably soluble, and the same is true in a less degree of magnesium carbonate. The monocarbonates of potassium and sodium are highly soluble, but the bicarbonates also appear in solution. Practically the carbonates of these alkalis usually become changed into other salts (sulphates, chlorides, etc.) and the carbon dioxide that may have been temporarily locked up with them is set free by the change, or enters some other combination. The magnesium and calcium carbonates are also in part changed to other salts. But for the purposes of this discussion, which is concerned chiefly with the final issue and not with the transient stages of these compounds, it is sufficient to note that the chief result of the decomposition of the original silicates is the formation of calcium and magnesium carbonates, which are deposited as limestones and dolomites and thus lock up carbon dioxide at the expense of the atmosphere. The amount so taken from the air in the known geological periods has been variously estimated at from 20,000 to 200,000 times the present content; indeed estimates have gone beyond the last figure. When it is considered that 44 per cent. of all pure limestone and a higher per cent. of all pure dolomite is carbon dioxide, it is obvious that the total quantity is very large, and its computation is dependent upon the estimate of the total amount of limestone and dolomite in the crust of the earth.

A second source of permanent loss consists of the consumption of carbonic acid by plants and the fixation of the carbon in carbo-hydrates, hydro-carbons and other carbonaceous compounds which ultimately take the form of coals, bitumens, oil, gas, and perhaps most important of all, disseminated organic matter in the sedimentary series.

Exceptions.—Some hydro-carbons have probably been produced by inorganic action, notably those derived from carbides

(Moissan) formed within the earth and extruded from it. Some carbonates probably have been formed by carbonic acid contained within the rocks or extruded from the interior. In certain phases of the problem, deduction is to be made for such carbonaceous compounds and carbonates as are formed in the sea by marine plants and other agencies which derive their carbonic acid from the sea water; but in the general discussion of the question, the carbonic acid of the sea must be reckoned in with the carbonic acid of the air, for the two are in equilibrium and constitute essentially and potentially one body. The necessity for this assumption will be more obvious when we come to discuss the function of the ocean in influencing the constitution of the atmosphere.

Sources of permanent gain.—Over against these sources of secular loss there are certain sources of gain. If the assumption that the constitution of the atmosphere has varied through only moderate limits within the known ages be adopted, it is necessary to postulate sources of supply of a competency approximately equal to the sources of loss. The data for such postulation are exceedingly unsatisfactory and a function of the hypothesis should be to stimulate investigation in these lines which have been barely touched by serious inquiry.

a. Gain from the interior.—The crystalline rocks of the surface of the earth have been shown by the recent examinations of Tilden ¹ to contain very notable quantities of gas, consisting of hydrogen in preponderance, carbon dioxide and carbon monoxide in large percentages, and nitrogen and marsh gas in small quantities, with water vapor, but with a practical absence of oxygen. Twenty-five analyses, including ancient and modern volcanic and even some metamorphic rocks, gave an average volume of gas equal to about four and a half times the volumes of the containing rocks. A computation on this basis shows that an atmosphere equivalent in mass to the present one would be contained in a very superficial rind of the earth, and that if this volume of

¹ On Gases Contained in Crystalline Rocks and Minerals: W. A. TILDEN, Chemical News, April 9, 1897.

included gases be constant for the whole body of the earth, it contains potentially a multitude of atmospheres.

It is a familiar fact that enormous quantities of gases are ejected from volcanoes during their active periods. It has been very generally assumed that these gases and vapors, among which steam vastly preponderates, have a surface origin, and there can be no doubt that this is true of some notable part; but, on the other hand, there is abundant ground for the belief that another notable part is brought from the interior and is a real contribution to the earth's atmosphere and hydrosphere. It may not be possible at present to demonstrate this, but inquiry in this direction is invited. There seem to be no means of estimating from present data even approximately the volume of gas which is given forth, but it is certainly large. There are grounds for believing that the gases of the interior escape by other than volcanic vents. The deep rending and sharp shock of the earth in seismic movements, the stresses and fissuring of readjustments, the disintegration of crystalline rocks, and the resources of slow diffusive penetration are among these. So far as the setting free of carbon dioxide by decomposition of the containing rock is concerned, it is to be noted that the chemical action which sets it free involves a consumption of carbon dioxide very greatly in excess of the amount liberated, so that, as computation will show, the total effect of the process is one of loss which the internal gases only very slightly modify. This, of course, is not true of mechanical disintegration.

b. Exterior sources of gain.—The meteorites which are constantly falling to the earth contain included gases, often in great volume. They also contain carbonaceous matter which is partially burned in passing through the air. The nature of the included gases is notably similar to those of the crystalline rocks, hydrogen and carbon dioxide being the leading constituents with nitrogen in very subordinate amount and free oxygen essentially absent.¹ Water vapor appears in both meteorites and

¹ See numerous papers of A. W. WRIGHT in *Am. Jour. Sci.*, notably *Gases contained in Meteorites*, *Am. Jour. Sci.*, 3d series, Vol. XII, No. 69, Sept. 1876.

crystalline rocks, but it is impossible to say how far it was absorbed from terrestrial sources. It has even been suggested that all the gases both of meteorites and of the crystalline rocks were simply absorbed from the air and not brought in from without; but their proportions are so different from those of the air that it would be necessary to assume an extraordinary selective power to make this possible; for oxygen must be wholly rejected as a gas; nitrogen, though greatly preponderant, must be almost neglected; carbon dioxide must be absorbed in great quantities relatively; carbon monoxide, though very rare in the atmosphere, must be taken in abundantly; while the hydrogen, which is scarcely detectable in the atmosphere, must be absorbed in superlative amounts. It is difficult to conceive how a meteorite passing rapidly through the air can have absorbed many times its volume of an element which does not appear in the air in detectable quantities. However, I am unable to say that the analyses were made sufficiently soon after the fall of the meteorites to make this point conclusive. But, at any rate, the hypothesis of selective absorption is confronted with grave difficulties and the alternate hypothesis that the gases are brought to the earth in the meteorites seems the more probable. The emanations from comets support the view that meteorites are charged with gases in extra-terrestrial regions. Here again inquiry is needed and experimental tests are obviously suggested.

If gases are brought in with meteorites, it is probable that independent molecules are flying through space and are caught up by the earth. The modern doctrine of molecular velocities, which holds that gases are liable to escape, and presumably are escaping constantly, from planetary bodies, carries the presumption that individual molecules are flying through space with some degree of frequency. Astronomical phenomena, to be sure, seem to indicate that the quantitative value of these cannot be very great, but as definite data are yet wanting and we are dealing with vast lapses of time and slow processes of depletion, making need for slow processes of accretion only, this agency may

deserve a place among the undetermined sources of atmospheric material.

It is among the possibilities that the sun itself may be a direct source of atmospheric feeding. The speed at which the solar prominences are projected from the sun has been observed to exceed the parabolic velocity of the sun;¹ that is, the rate of projection is such that if the outer atmosphere of the sun does not effectually interfere, the gases are shot away beyond even the sun's control. A much less speed could carry the gases to the earth, so that, unless the outer atmosphere of the sun interposes effectual barriers, it is not improbable that gases are thrown as far out as the orbit of the earth. The earth probably cannot hold hydrogen, the chief gas of these prominences, permanently as such, but it may do so when combined with oxygen. The shooting of solar hydrogen through our atmosphere would lead to the formation of water, because, even at ordinary temperatures, such of the molecules of oxygen and hydrogen as collided with the requisite velocity would enter into union. There seem therefore grounds for placing this among the possible but undetermined sources of supply for our atmosphere and hydrosphere. When the mystery of the zodiacal light and the gagenshein shall be solved, it is possible that demonstrative evidence of our relations to the extreme projections of the solar atmosphere may be available.

In the present state of extreme uncertainty relative to all these possible sources of supply, a hypothesis which necessarily involves them proceeds with uncertain steps and must perforce wait patiently for more definite determinations, but the pressing of a hypothesis which lays emphasis upon them is but giving effect to the fundamental mission of all working hypotheses.

VARYING RATES OF ACTION

By the terms of the hypothesis the state of the atmosphere at any time is dependent upon the relative rates of loss and gain.

¹ The Story of the Sun, by SIR ROBERT BALL, pp. 185-188; The New Astronomy, LANGLEY, p. 61.

It is of supreme importance therefore to consider irregularities in the action of the sources of loss and gain.

Varying rates of gain.—The constancy or irregularity of the sun's contribution—assuming it to make a recognizable contribution—is quite unknown. It would presumably be dependent upon the internal explosive action of the sun concerning which all thought is as yet highly speculative. So far as its relations to geological periods are concerned, it would probably be either an essentially constant factor or one which would not fall in systematically with any special phase of geological progress, and could not be regarded as a coöperative factor in any definite phase. It might be progressively increasing, as the sun concentrates, or progressively diminishing.

Much the same is to be said with regard to possible sources of supply from meteoric and similar extra-terrestrial sources.

The extrusion of gases and vapors from the interior has been presumably periodic, because the conditions of molten eruption and of mechanical disruption have probably been periodic rather than constant. No specific determination of the periodicity of volcanic action has yet been made out, but the testimony of present geological data is to the effect that vulcanism has been more frequent and intense at certain periods than at others. This is clearly true for individual grand divisions of the earth, and seems to be true of the earth at large, notwithstanding the fact that vulcanism was a more or less local phenomenon. While a definite periodicity, specifically connected with other phenomena, cannot now be affirmed, the tentative proposition that vulcanism has been more abundant in great periods of readjustment than in periods of quiescence may be entertained. The connection with those periods seems sometimes to have been very intimate and immediate, and at other times more remote. So far as disruption of the rocks constitutes a means of escape for internal gases, there should obviously be a close connection with periods of readjustment. In a rather general and uncertain way, then, it would seem necessary to assume, in a working hypothesis, that the enrichment of the atmosphere from internal

sources has proceeded more rapidly at or about the periods of crustal disturbance. This, as we shall see, coincides practically with the periods of depletion from atmospheric action on the surface, and hence, so far forth, the two processes tend to neutralize each other and preserve the constancy of the earth's atmosphere. The hypothesis must therefore recognize that it was only when one agency fell behind the other in its competency that its specific results became manifest, and then only by the difference in their respective effects.

Varying rates of loss.—The rate of chemical action of the atmosphere on the surface of the rocks is believed to have been intimately connected with the extent and height of the land area, considering the earth as a whole. There were qualifying conditions, as we shall see, but notwithstanding, this is regarded as an important law. It is made a fundamental postulate of the hypothesis, and the vitality of the hypothesis as a working instrument of investigation hangs very largely upon it. It is obvious that the greater the surface area of rock exposed to the effective action of the atmosphere, the more rapid will be the rate of disintegration, other things being equal, and the more rapid the consumption of carbon dioxide. ¹

The rate of carbonation of the rock is dependent upon elevation as well as superficial area. The disintegration of rock is the most active by far in the zone lying between the surface and the level of permanent underground water, technically the water table. It is in this zone that the atmosphere and the moisture of the earth combine to give the greatest chemical

¹ Oxygen is also consumed in the decomposition of average rock, but in less amount than carbonic acid, and as the amount of oxygen in the air is very much larger than that of carbon dioxide, the part consumed is far less critical. In an exhaustive study of the constitutional history of the atmosphere, the loss and gain of oxygen must be considered, and certain very interesting and important phases of atmospheric variation are probably connected with the production and consumption of the oxygen, but, as indicated, they are much less immediate and critical in the consideration of thermal problems with which our hypothesis is more especially concerned, and for the sake of simplicity the oxygenation of the rocks may be temporarily neglected; and for like reasons the many minor reactions may also be ignored and attention confined to the carbonation.

activity. It is established by the most ample observation in mining, that below the permanent water level disintegration has made slow progress compared with that in the zone above the water level. Now the thickness of the zone between the surface and the permanent water level is intimately dependent upon the general altitude. In a continent reduced approximately to base level, this zone is exceedingly thin. In a region much elevated and deeply dissected by erosion, the thickness of the zone is very much greater. As between a continent with an average elevation of 2000 feet, at the climax of dissection following a crustal readjustment, and a continent of similar area with an average elevation of 300 feet, during a period when it is approximately at base level, the average depth of the aerated zone above the water level, probably varies more nearly with the square of the elevation than as a direct multiple of it. It is improbable, however, that the chemical action is augmented at so great a ratio. Probably greater warmth and more abundant vegetation are correlated with the lower altitudes, and both these aid chemical action. This in turn is somewhat offset by the greater mechanical disaggregation which results from changes of temperature and from gravitative influence in the more elevated condition. Making all allowances that seem required for the offsetting factors, it would still appear that the elevated condition increases the activity of decomposition in a very notable degree.

Below the permanent water level, the advantage probably also lies greatly with the higher elevation. The action of surface water upon the deeper rock is dependent upon the unbalanced hydrostatic pressure which promotes underground circulation and forces the water through the crevices and pores of the rock. If the underground water stands near sea level, there is little unbalanced hydrostatic pressure to promote active circulation and thereby carry the surface waters, enriched with atmospheric gases, down into the lower strata and bring them into action. The atmospheric waters precipitated upon the surface run away chiefly at the surface, and fail of the contact necessary for action. On the other hand, in an elevated region

there is a potential hydrostatic pressure measured by the difference of altitude of the surface of the ground water and the surface of the sea which tends to cause the waters to flow through the rock and thus find a tortuous way to the equilibrium of the sea level. A deep underground circulation is therefore a function of high altitude, and, correlated with that circulation, is chemical activity proportionate to the enrichment of the surface waters with chemically active agencies, in the present instance, carbon dioxide in particular. This deeper circulation, correlated with hydrostatic pressure, is enhanced by the greater degree of fissuring of the rock which attends elevated tracts, for in the process of elevation, writhing and cracking are notable incidents, and, in addition to this, the gravitative tensions which necessarily attend an elevated position lend their aid in the production and opening of crevices. Precisely the opposite conditions prevail at low levels. The protruding superficial portion of the land is the most fissured part and when it has been cut away by erosion the basal remnant is normally less open to the penetration of water. It would appear from a consideration of these several associated influences that disintegration and decomposition are facilitated by elevation in a very important degree.

If, therefore, there were times in the history of the earth when there were general readjustments of its bodily form to accumulated internal stresses, resulting in extensive elevations, embracing not only the formation of mountains and plateaus, but the general warping outwards of the continental platforms, and the bowing downwards of the ocean basins, attended by the withdrawal of the sea, so that the land area was extended and, at the same time its average elevation increased, and a portion of it rent and crushed, it is believed that the carbonation of the rocks must have been accelerated by some notable multiplier and that the rate of consumption of the carbon dioxide of the atmosphere must have been correspondingly promoted; and this is made an important postulate of the hypothesis.

At least two periods of such very general and notable

elevation appear to be well authenticated by present geological data, imperfect as they are for certain quarters of the earth. These periods occurred near the close of the Paleozoic and of the Cenozoic eras respectively. Closely connected with these two periods are two well authenticated glacial periods.

If, on the other hand, there were periods of prolonged quiescence of the earth's body during which the lands were cut down well towards base level, they would be accompanied by a progressive slackening of the rate of disintegration, and a corresponding reduction in the rate of atmospheric loss of carbonic acid, giving opportunity for the agencies of repletion to overtake and surpass the agencies of depletion. It is believed that there was a series of such periods among which the Cretaceous is best authenticated.

During a prolonged period of relative quiescence the encroachment of the coast lines upon the land, if elevated, becomes notable. In addition to this, the material removed from the land and deposited in the sea raises the water level, and when the degradation is notable this rise amounts to an appreciable factor. This aids the coast action by lifting it above the restraining influences of its own products, which, by shoaling the water off shore, tend to break the force of wave action. The notion is also entertained that during periods of readjustment the continental masses are apt to be lifted beyond the plane of perfect isostatic equilibrium, and that there follows a tendency to slowly creep back into equilibrium, accompanied by a general tendency of the continental platform to flatten out under gravitative stress. The continental platforms are to be regarded as having elevations above the abysmal ocean bottom of perhaps 12,000 feet, and, as their average gravity is two and a half to three times that of the water which surrounds them, there remains a large excess of gravitative stress tending to cause the continents to spread laterally.

The combined effects of these agencies is a transgression of a thin edge of the sea upon the land. Now, such extensive transgression took place on all the great continents in the Upper

Cretaceous period, and this fact may be taken as indicating that the planation which reached so pronounced an expression on the American continent at that period affected nearly or quite all the continents in some similar measure. An inspection of the whole range of geological history shows periods of similar transgression accompanied by the development of luxurious and cosmopolitan marine faunas of the shallow-water type which in themselves imply the conditions here postulated.¹

If this be a correct view it is obvious that at such periods the areas of land exposed to atmospheric action were notably reduced by sea encroachment, and that at the same time the lowness of the land greatly limited the depth of atmospheric activity by reducing the zone between the surface and the water-table and by reducing the hydrostatic penetration of surface waters. As already remarked, there is to be counted in offset probably warmer temperature, a higher degree of moisture, and a more abundant vegetation, but it is not believed that this approaches, even remotely, to a full offset to the reduction due to low elevation and reduced area.

If the foregoing views are correct there were certain periods in the history of the earth when carbonation proceeded with multiplied activity, separated by other periods during which its activity was greatly reduced. The intensification and the reduction differ by some notable multiplier of the average rate.

In working application, the hypothesis tentatively recognizes as periods of land extension attended by rapid carbon dioxide consumption, (1) the close of the Silurian and the opening of the Devonian, (2) the Permian and early Triassic, and (3) the Pliocene and Pleistocene. To this category may perhaps also belong, though the evidence at present is less adequate, (4) the early Cambrian, (5) the closing Ordovician and opening Silurian,

¹ For further statement of these views, see *The Ulterior Basis of Time Divisions and the Classification of Geologic History*, JOUR. GEOL., Vol. VI, No. 5, July-August, 1898, pp. 449-462; *A Systematic Source of Evolution of Provincial Faunas*, JOUR. GEOL., Vol. VI, No. 6, Sept.-Oct., 1898, pp. 597-608; *The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere*, *ibid.*, pp. 609-621.

(6) the close of the Jurassic and the opening of the Lower Cretaceous, and (7) the transition period between the Cretaceous and the Eocene. In these periods there are evidences of declared intensifications of climatic influence expressed in widespread and thick deposits of salt and gypsum and in great series of red sandstones and marls, and, in the two most notable cases, by pronounced glaciation in middle and low latitudes.

On the other hand, it regards the following as periods of sea extension attended by the active freeing of carbon dioxide through the agency of prolific lime-secreting life, as hereafter set forth: (1) the middle Ordovician, (2) the middle Silurian, (3) the sub-Carboniferous, (4) the late Jurassic, (5) the Upper Cretaceous, and (6), less notable, the later Eocene and earlier Miocene. During these periods there is evidence of extensive limestone deposition spreading out widely on the continental platforms, attended by very mild and equable climates very nearly uniform for all latitudes.

SOURCES OF TEMPORARY LOSS AND GAIN

The discussion has thus far taken note of the original carbonation of the silicates of crystalline rocks only. These crystalline rocks, according to Dr. Tillo,¹ occupy something over 20 per cent. of the surface of the land. There remains nearly 80 per cent. occupied by secondary rocks which now claim attention.

Sources of temporary loss—The function of the secondary deposits.—To a large extent the material of the secondary deposits underwent chemical decomposition and carbonation preliminary to its deposition, indeed as a prerequisite to its derivation. In so far as this process was incomplete in the earlier stages, it was continued during any subsequent state of exposure, but this action belongs under the preceding head of original carbonation.

In the erosion of tracts of secondary rocks the limestones and dolomites are dissolved and carried down to the sea essentially as bicarbonates. In the strata they existed as monocarbonates. Their solution involves the taking up of a second

¹ Berghaus Atlas.

equivalent of carbonic acid to render them bicarbonates, and this second equivalent is derived essentially from the atmosphere. There is herein a source of temporary loss, temporary because the second equivalent of carbon dioxide remains associated with the bases in the sea only until deposition takes place, when it is set free. It is to be noted that a second equivalent is also taken up in the formation of original carbonates if they are dissolved. As the crystalline rocks occupy only a little more than 20 per cent. of the land surface and are probably not removed as fast as the secondary rocks, not more than about one fifth, probably not more than one tenth, of the bicarbonating carbon dioxide is associated with original carbonation. The remaining four fifths or more are occupied in bicarbonating and dissolving the calcareous and magnesian portions of the secondary rocks. It follows that the ratio of carbon dioxide now taken out of the atmosphere as second equivalent in any unit of time, to that taken out as first equivalent, is probably fully five to one, and not unlikely as high as ten to one. This ratio would not necessarily hold for past periods, but in all those under consideration the second equivalent was undoubtedly very much greater than the first.

Accepting, for the purposes of a rude estimate, the data of T. Mellard Reade,[†] the amount of carbon dioxide removed annually by original carbonation, reckoned by proportional area, is 270 million tons, the amount temporarily removed as the second equivalent of the bicarbonates is 1350 million tons; the amount simply transferred from the land to the sea as the first equivalent of the carbonates previously formed is 1080 million tons; the total mass taken from the atmosphere annually being therefore 1620 million tons, and the total mass removed to the sea 2700 million tons. Besides uncertainties in the original estimate of Reade, the first item is subject to correction (probably large) for the slower rate of disintegration of the crystalline rocks. This is, however, somewhat offset by weathering action on the silicates that remain undecomposed in the secondary rocks, and on

[†] Addresses, Geol. Soc. of Liverpool, 1876 and 1884, quoted in Dana's Manual, p. 191.

the late volcanics which are not all included in the 20 per cent. of the land area reckoned as crystalline. The second item is subject to correction to the extent that the salts were normal carbonates and not bicarbonates.

Reciprocal sources of temporary gain.—The second equivalent of the carbonates in the ocean is subject to easy removal under suitable conditions, and reënriches the atmosphere by diffusion into it from the ocean. The conditions under which this is set free are of critical importance to our hypothesis. We have to consider (*a*) saturation, (*b*) chemical reactions and dissociations, and (*c*) organic action.

a. Absence of general saturation.—In the absence of other agencies of removal the accumulation of calcium bicarbonates in the ocean would go forward to the point of saturation, if there were a sufficient amount producible. It would then be deposited as limestone, and the second equivalent of the carbon dioxide would be set free. There is little reason to think, however, that general saturation has been reached during the known portion of the earth's history. In local basins subject to peculiar conditions, saturation certainly has been attained, as the marls of the great saliferous deposits testify. The present approach to oceanic saturation in calcium carbonate is apparently only about 40 per cent. If the ocean in former times had reached saturation in calcium carbonate and any notable precipitation had followed, the precipitate should appear as a distinctive constituent of the clastic deposits. While calcareous matter which might be so interpreted occurs in some of these deposits, there is a notable absence of anything of the kind in many others where it might be expected, and the general character of the sandstones and shales seems more concordant with the accepted view that they were laid down in waters that did not, except in special cases, directly deposit calcareous matter. In view of the probable presence of lime-secreting organisms, the problem is generally rather to account for the paucity of calcareous matter than its abundance in the clastic deposits. The explanation is doubtless found in the undersaturation of the sea water and its ability

to dissolve calcareous relics. This view is supported by the partially dissolved condition in which calcareous fossils are so commonly found in the sediments of practically all the ages. The inference, therefore, to be drawn from the character of the sediments, and from the partial solution of calcareous fossils, is that the ocean, as a whole, has not generally been saturated with calcium bicarbonate during its known history. Murray has made us aware that at the present time the greatest depths of the ocean dissolve calcareous relics so freely as to prevent their accumulation.

b. Inorganic chemical reactions.—Viewed comprehensively the sea water consists of such solutions as have been carried down from the land in past times, modified by concentration and deposition. No important constituent has been totally removed. The land and sea waters have therefore the same fundamental constitution, but the salts of the former enter the sea in a more dilute form and in different proportions from those contained in the latter. Aside from organic action, and from exceptional inorganic agents such as may arise from submarine volcanic action and like incidental sources, essentially all occasion for chemical reaction when land waters are added to sea waters, is limited to a readjustment of the equilibriums of the common constituents of the two commingling waters. Following the simple doctrines of the old familiar “chemistry of results,” the addition of a dilute solution of salts of the alkalis and alkaline earths to a more concentrated but not saturated solution of the same salts would neither occasion precipitation nor the evolution of gas, for every acid is mated with a base, and all are much below the point of saturation. According to the old interpretation the bases of the sea salts are, in the main, mated to stronger acids than those of the land waters, and these combinations will not be changed on the entrance of the latter. So, also, the small amounts of strong acids of the land waters are already mated with the strong bases in the main, and largely form the same combinations as those of the sea waters. Such interchanges as follow involve a double reaction essentially without the freeing

of acid or base. Under the old method of interpretation the sea salts, according to Dittmar, consist of—

	Percentage	Total Tons
Sodium chloride - - -	77.758	$35,990 \times 10^{12}$
Magnesium chloride - - -	10.878	$5,034 \times 10^{12}$
Magnesium sulphate - - -	4.737	$2,192 \times 10^{12}$
Calcium sulphate - - -	3.600	$1,666 \times 10^{12}$
Potassium sulphate - - -	2.465	$1,141 \times 10^{12}$
Calcium carbonate - - -	0.345	160×10^{12}
Magnesium bromide - - -	0.217	100×10^{12}
	100.000	$46,283 \times 10^{12}$

A rude average of the composition of land waters and of the amounts of salts carried to sea annually, founded on the estimates of T. Mellard Reade, is here given for comparison.

	Approx. percentage	Tons annually
Calcium carbonate - - -	50	$2,700 \times 10^6$
Calcium sulphate - - -	20	$1,080 \times 10^6$
Magnesium carbonate - - -	4	216×10^6
Magnesium sulphate - - -	4	216×10^6
Sodium chloride - - -	4	216×10^6
Potassium and sodium, Sulphates and carbonates }	6	324×10^6
Silica - - -	7	378×10^6
Other substances - - -	5	270×10^6
	100	$5,400 \times 10^6$

These tables do not embrace the second equivalent of carbonic acid.

From these data it appears that it would require only a little over eight and one half million years for the land waters to bring in a gross amount of salt equal to that of the ocean, but it would require very different periods to bring in the individual constituents. It would take 166 million years to bring down the sodium chloride, but only about 1.5 million years to bring down the calcium sulphate, and only about 60,000 years to bring down the calcium carbonate. It appears therefore that there must be agencies constantly removing the calcium carbonate and the calcium sulphate at relatively high rates. These particular figures are subject to all the uncertainties involved in

Reade's primary estimate, but they probably represent approximately the relative ratios, and show the general nature of the eliminations that are requisite to change accumulating land waters into sea waters.

While these general statements of the nature and limitations of chemical action, based on the more familiar doctrines of the older chemistry, are doubtless essentially true, the refinements of modern chemistry teach that there is an intricate series of dissociations and exchanges of acidic and basic factors, and of the various ions, in an effort to establish and maintain a new equilibrium between the salts, required by their new proportions and their new states of dilution. As the land waters contain a relatively large percentage of bicarbonates of calcium and magnesium, the readjustment affects these especially, with the result that probably a minor percentage of the second equivalent of carbon dioxide is set free. It seems necessary to state this with qualification on account of the extreme complexity of the reactions, and the incompleteness of existing data; but the Challenger, and similar investigations show that the quantity of second equivalent of carbon dioxide is less than sufficient to raise all of the carbonates into bicarbonates. This deficiency is apparently limited to 20 per cent. or less of the theoretical amount required. More rigorous experimental determination is, however, greatly needed.

It is probable that the second equivalent of the land waters is deficient in some like degree, but this has not been experimentally determined. If this be true, it must reduce the estimate of the carbon dioxide brought down to sea, and also the amount set free by dissociation. The total amount of carbon dioxide which may be supposed to be set free by inorganic reaction in the sea in its present state of concentration, is therefore probably much less than 20 per cent. It is obvious from the preceding considerations, and others that will follow, that to maintain the atmospheric status even approximately there must be a nearly or quite complete return of the second equivalent of carbon dioxide by some means. This is also implied by the fact that

the oceanic deposits are not bicarbonates in any notable degree. The chief agencies of this return are held to be organic, and will be considered presently.

The chief compounds of both the land and sea waters are sodium, potassium, magnesium and calcium chlorides and bromides; sodium, potassium, magnesium and calcium sulphates; sodium, potassium, magnesium and calcium carbonates and bicarbonates; in other words, every combination which may take place between the acids and bases involved. Besides these salts there are, theoretically at least, the several acids and bases and a complete series of ions as well. There is a continuous dissociation and reunion in the effort to maintain equilibrium. The extent of the dissociation is dependent, among other things, notably upon the degree of concentration of the solution and upon its temperature. In an especial degree the extent of the freeing of the second equivalent of carbon dioxide is believed to be dependent upon this dissociation as influenced by temperature, and it is thus a vital consideration in realizing the function performed by the ocean during glacial episodes when its temperature was greatly changed. This function is made the subject of a special study in the paper of Mr. Tolman in this number of the *JOURNAL*.¹

Mr. Tolman's studies have been founded upon Dittmar's experiments, and seem to show that the amount of carbonic acid freed from the bicarbonates by dissociation is very sensibly influenced by such changes of temperature as are necessary, according to the deductions of Dr. Arrhenius, to produce extended glaciation, on the one hand, and a mild climate in the arctic regions, on the other. In this he finds support for the suggestion which I made in a previous paper² that the ocean during a glacial episode instead of resupplying the atmosphere, in the stress of its impoverishment, would withhold its carbon dioxide to a certain extent, and possibly even turn robber itself. On the other hand, when the temperature is rising after a glacial

¹ Pp. 585-618.

² A Group of Hypotheses Bearing on Climatic Changes, Vol. V, No. 7, 1897, p. 682.

episode, dissociation is promoted, and the ocean gives forth its carbon dioxide at an increased rate, and thereby assists in accelerating the amelioration of climate.

c. Organic action.—The elimination of the vastly preponderating percentage of calcium salts in the land waters, involving a reduction from 70 per cent. in these to less than 4 per cent. in sea waters, is assigned mainly to marine life. With the calcium sulphate we do not seem to be specially concerned here except so far as indirectly it may become involved in the reactions which eliminate the calcium carbonate. It would appear obvious, however, from the fact that its ratio is reduced from about 20 per cent. in the land waters to about 3.6 per cent. in the sea waters that it suffers much secular loss. The reduction of the calcium carbonate from about 50 per cent. in the land waters to about one third of 1 per cent. in the sea waters is a fact of prime importance.

The amplest and most familiar geological observation shows that the elimination takes place mainly as normal carbonate of lime in the form of shells and skeletal parts of various marine animals, and of some plants. The gross fact of observation is the disappearance of great quantities of calcium bicarbonate from the water, and its reappearance as the secretions of animals and plants in the form of normal carbonate. Whatever may be the specific steps involved in their life economies, it seems essentially immaterial to consider here whether the animals and plants take their lime directly from the calcium carbonate, and set its surplus carbonic acid free, or whether they take it from calcium sulphate, and by using carbonic acid, derived ultimately from the waters also, convert it into carbonate, setting free the sulphuric acid to attack in turn the calcium carbonate of the sea, and thus by circuitous process free its carbonic acid, or whether the procedure follows any other indirect course; for the final result, when balanced all around, seems to be essentially the same. It may even trench on the organic cycle without essentially changing the final result. The important thing to be observed is that the process is dependent upon sea life, and varies with its

activity. There is no free supply of any competent discharging agency independent of sea life.

Variations of lime-secretion by sea life.—The amount of lime-secreting sea life is greatly influenced by the temperature of the sea and by favorable habitat. Lime-secreting sea life, both plant and animal, is greatly favored by high temperature and reduced by low. In support of this the following statements from the Challenger Report¹ and other sources may be offered, in which I have italicized the significant parts :

Species of algæ which secrete carbonate of lime are abundant in the *shallow waters* of the ocean. In the *tropical regions* especially there are massive species of *Lithothamnion*, *Lithophyllum*, *Halimeda* and other genera that make up a large part of some coral reefs and of the surrounding coral sands and muds. *Two hundred fathoms* is probably the extreme limit at which any of these organisms live in the ocean.

Rhabdospheres are especially developed in *equatorial* and *tropical regions*, and are *rarely* met with in regions where the temperature of the surface water falls below 65° F. (18.3° C.). Coccospheres, while abundant in tropical waters, are found further north and south than the Rhabdospheres; they are present even where the temperature on the surface is as *low as 45° F.*, (7.2 C.); indeed, Coccospheres attain their greatest development in *temperate regions*. These organisms are absent or *rare in coast waters* affected by rivers; they especially flourish in the pelagic currents of the open ocean. . . . In *Arctic and Antarctic waters* Coccospheres and Rhabdospheres are replaced by similar minute algæ *which do not, however, secrete rods and disks of carbonate of lime on their outer surfaces.*

Rhabdoliths and Coccoliths—the broken down parts of Rhabdospheres and Coccospheres—play a most important part in all deep-sea deposits, *with the exception of those laid down in polar and subpolar regions.*

Of all the organic remains met with in marine deposits, by far *the most frequent are the shells of Foraminifera*; it may be safely said that these organisms or their fragments are present in every average sample of marine mud, clay, ooze or sand. . . . *Nearly all the species are confined to tropical and subtropical waters; they gradually disappear from the surface-nets as the polar regions are approached, the dwarfed forms Globigerina pachyderma and Globigerina dutertrei, being the only species met with in Arctic and Antarctic waters. . . . In the calcareous oozes from tropical regions, the shells of all the species inhabiting the surface waters are observed in enormous abundance, but these same species are never met with in deposits from polar regions. . . .*

¹ Challenger Report, Deep Sea Deposits, pp. 257, 258–261, 263, 31 and 266.

There are not more than twenty or twenty-two species of pelagic Foraminifera, yet so numerous are the individuals of the species that they usually make up over 90 per cent. of the carbonate of lime present in the calcareous oozes of the abysmal regions of the ocean. . . .

The bottom-loving Foraminifera—those belonging to the Benthos—are *more abundant in the shallow water*, than in the deep-sea deposits, and occasionally a single species may occur in such abundance in shallow depths in some regions as to make up the greater part of a deposit. . . .

The presence of large numbers of Pteropod and Heteropod shells indicates tropical or subtropical regions, and relatively shallow depths. Abundance of the shells of pelagic Foraminifera indicates the same regions, but when found without the shells of pelagic mollusks they indicate a greater depth than when these latter are present. . . . The presence or absence, and the size of Rhabdoliths, Coccoliths and Coccospheres *give important indications as to latitude and depth*—the first predominating in tropical regions, the two latter being better developed in temperate regions, and *all disappear from the deposits as the polar waters are approached.*

A large number of these pelagic mollusks (Pteropod and Heteropod) *secrete carbonate of lime shells, and this is especially the case in tropical waters.* In polar regions the place of the shelled species is taken, with the exception of one or two small species of Limacina, by a *shell-less species.* The shells of the tropical species make up a large part of some tropical and subtropical deposits from moderate depths, in which there is a relatively small quantity of land débris. *Like the pelagic Foraminifera these pelagic Mollusca attain their greatest development in the warm oceanic currents, and diminish both in the number of species and the size and mass of the shells as the colder currents of the polar regions are approached.*

Reef-forming corals are confined to waters which, through even the coldest month, have a *mean temperature not below 68° F.* Under the equator the surface waters in the hotter part of the ocean have the temperature of 85° F. in the Pacific, and 83° F. in the Atlantic. The range from 68° to 85° is, therefore, not too great for reef-making species.¹

An isothermal line crossing the ocean where this winter temperature of the sea is experienced, one north of the equator, and another south, bending in its course toward or from the equator, wherever the marine currents change its position, will include all the growing reefs of the world; and the area of waters may be properly called the *coral-reef seas.* . . .

*Over the sea thus limited coral reefs grow luxuriantly, yet in greatest profusion and widest variety through its hottest portions.*¹

I have found no specific statements relative to the dependence of common mollusks on temperature, but the enumeration of the

¹ DANA: Corals and Coralline Islands, p. 83.

species in different latitudes clearly indicates that they are less abundant in the arctic provinces than in the tropical, from which it may perhaps be safely inferred that the lime-secreting function of the mollusks is increased by warm temperature.

In the foregoing quotations references are made to the preference of certain forms for shallow waters. The great preponderance of lime-secreting species on the shoal areas—100 fathoms or less—is too familiar to need emphasis.

In other articles¹ I have endeavored to show that there were certain stages in the earth's history when the seas were extended widely over the continental platforms, affording conditions extremely favorable to the multiplication of lime-secreting shallow-water life. I endeavored to connect these, on an observational basis, with the great limestone-producing epochs of geological history and to show that these were correlated with genial climates over high and low latitudes alike. On the other hand, I endeavored to show that there were other periods during which the land area was increased and the sea restricted, resulting in a great reduction of this normal habitat of the chief lime-secreting forms of life. I endeavored to show that so far as the lime-secreting life is concerned, the freeing of carbonic acid was promoted during periods of extended seas and that it was retarded during periods of extended land. This holds good when considered simply from the standpoint of available area, but it becomes still more true if, as this hypothesis maintains, the extension of sea-area was correlated with favorable temperature, while the restriction of sea-area was correlated with adverse temperature. The only pelagic life that enters much into the problem is that which occupied the superficial waters of the open ocean. The area of this increased and diminished concurrently with the extension and contraction of the sea.

¹ A Systematic Source of Evolution of Provincial Faunas, *JOUR. GEOL.*, Vol. VI, No. 6, pp. 597-608.

The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere, *JOUR. GEOL.*, Vol. VI, No. 6, pp. 609-621.

THE FORMATION OF ORGANIC COMPOUNDS AS AN AGENCY OF
ENRICHMENT AND DEPLETION

The familiar fact that plants produce complex carbon compounds at the expense of the carbonic acid of the air, and that animals, aided by plants, by combustion, and by decay, decompose these compounds, and return a portion to the air as carbonic acid need not be dwelt upon. These reciprocal processes constitute a cycle which, in so far as it is mutually compensatory, affects the constitution of the atmosphere only in temporarily locking up carbon in the transient organic matter. The cycle, however, is not complete at any time, and has fallen far short of being complete at certain times. A portion of the carbon compounds are not reconverted into carbonic acid, and this residuum has been sealed up in the strata, and represents so much of depletion of the atmosphere. When this residuum was large there was a hastening of the process of robbing the atmosphere. When it was small it put less tax upon the agencies of supply. In its concrete application, the hypothesis recognizes one notable period of residual accumulation, the Coal Measures. Subordinately it recognizes others, as the Huronian and the late Cretaceous. Perhaps the Coal Measure period is the only one in which the excess of carbon composition over decomposition was so great as to seriously influence the constitution of the atmosphere, considered by itself alone, though this is open to question. A computation of the carbonic acid locked up in coal and similar carbonaceous deposits compared with that locked up in the limestones shows that the former is greatly inferior to the latter, from which it is inferred that the organic factor has been much the less influential in producing variations of atmospheric constitution, *per se*, than through its relations to the carbonates.

Respecting the organic cycle itself, it is obvious that when the sum total of vegetable and animal life increases, the amount of carbonic acid locked up in the living organisms is increased, and *vice versa*. The total mass of all the vegetable and animal living matter on the earth is some small fraction of the total

amount of free carbon dioxide. It does not seem possible now to arrive at any closely approximate estimate of this ratio. Johnson² expresses the belief that the growth of plants would exhaust the carbonic acid of the atmosphere in 100 years if there was no return. The average length of time during which plant products remain as living tissue is probably greater than one year, and much less than ten years, which would make the total amount of the carbonic acid so locked up a quite small per cent. of that in the air. The amount of carbon locked up in the tissue of marine life which probably was not embraced in Johnson's estimate, would somewhat notably increase the figure, but if oceanic life is considered, the free carbonic acid of the ocean must be considered also which would greatly reduce the ratio.

A study of the life of the geological periods seems to indicate that there were very notable fluctuations in the total mass of living matter. To be sure there was a reciprocal relation between the life of the land and that of the sea, so that when the latter was extended upon the continental platforms and greatly augmented, the former was contracted, but notwithstanding this it seems clear that the sum of life activity fluctuated notably during the ages. It is believed that on the whole it was greatest at the periods of sea extension and mild climates, and least at the times of disruption and climatic intensification. This factor then acted antithetically to the carbonic acid freeing previously noted, and, so far as it went, tended to offset its effects.

THE FUNCTION OF THE OCEAN AS AN ABSORBENT OF CARBON DIOXIDE

The atmosphere penetrates the ocean by simple diffusion according to the laws of gas diffusion, modified slightly by hydrostatic pressure, and this must be considered in close computations, but is too small a factor to seriously affect the larger issues.

² *How Plants Feed*, p. 47.

Absorption of carbonic acid.—Independently of this the ocean has a specific power of absorbing carbonic acid. It is important to note that this power of absorption is greatly affected by temperature, as shown by the following table of the variations for *pure* water:¹

1	volume of water at	0°	dissolves	1.7967	volumes of carbon dioxide.
1	"	"	"	5°	"
1	"	"	"	10°	"
1	"	"	"	15°	"
1	"	"	"	20°	"
				1.4497	"
				1.1847	"
				1.0020	"
				0.9014	"

The precise rates of absorption for sea water are not accurately determined, and, indeed, are determinable with difficulty because, experimentally, they are complicated with the "loose" carbonic acid of the bicarbonates which is liable to be constantly freed by dissociation. The rates appear to be something less than those that obtain in pure water. Mr. Tolman has discussed this factor in his paper already referred to.

Release of absorbed carbonic acid.—Theoretically both the carbon dioxide diffused through the ocean and that dissolved in it should be in equilibrium with that of the air. Its quantity is dependent upon the temperature of the ocean and upon the partial pressure of the carbon dioxide of the air. Whenever the temperature of the ocean is raised a portion of its dissolved carbon dioxide is given forth. Whenever the partial pressure of the carbon dioxide of the air is reduced a portion of the free carbon dioxide in the ocean diffuses forth to reëstablish the equilibrium. The tendency to equilibrium is always present, though the constant variations of temperature and partial pressure prevent its complete realization at any particular time. If there were no counteracting influence the free carbon dioxide of the ocean would act as though it were a part of the air, and as the carbonic acid of the latter was consumed, that of the former would come forth into it.

But with loss of atmospheric carbon dioxide there is a reduction of temperature, and this increases the absorptive power of

¹Treatise on Chemistry, Vol. I. ROSCOE and SCHORLEMMER, p. 724.

the ocean, which then tends to prevent the escape of the carbonic acid. Low temperature is, therefore, antagonistic to atmospheric resupply. Mr. Tolman has attempted to ascertain the relative value of increased absorptive power and reduced partial pressure, and, though the data are insufficient for final conclusions, finds them about equal. The withdrawal of carbon dioxide from the air does not therefore call forth a proportionate amount of free carbonic acid from the sea. Indeed, it calls forth so little that the rate of atmospheric depletion is probably not appreciably retarded by it.

Summation.—Before proceeding to make special application of the hypothesis to the recognized glacial periods it may be serviceable to bring together into briefer statement the fluctuating features of atmospheric gain and loss.

1. Of the agencies of original or permanent supply, the internal group have probably fluctuated in some rude proportion to the disruption of the crust of the earth; the external group are beyond tangible treatment, but for aught that appears may be regarded as essentially uniform.

2. Of the agencies of permanent depletion, the conversion of silicates into carbonates (the chief factor) is assumed to have fluctuated essentially with the extension and restriction of the land; the formation of carbonaceous deposits fluctuated with the well-known conditions that presided over coal accumulation.

The agencies of permanent supply and of permanent loss are both regarded as rather slow in action and as being on the whole mutually compensatory, and indeed as being in some degree self-regulative since increase of supply naturally increases consumption and reduction of supply ultimately reduces the consumption; but these relations are believed to be subject to sufficient fluctuation to give a basis for pronounced climatic changes.

The sources of temporary supply and waste are much more rapid in action and apparently more intense and voluminous in results within any brief period.

1. The sources of temporary loss are: (*a*) the locking up of carbon dioxide in bicarbonates while in solution as their second

equivalent (the great factor); (*b*) the absorption of carbon dioxide in sea water; and (*c*) its consumption in forming organic matter.

The first and greatest of these is definitely connected with extension and elevation of the land, and the second is largely a sequel to it, dependent upon the temperatures it induces, while the third does not usually coöperate with these two, but rather, to the extent of its limited competency, offsets them.

2. The sources of temporary enrichment embrace: (*a*) the discharge of the second equivalent of carbon dioxide in the sea by life action (the great factor), and (*b*) by dissociation; (*c*) the diffusion into the air of carbonic acid absorbed in the sea water due to higher temperature antagonized by reduced partial pressure, and (*d*) the freeing of carbonic acid both in the air and the ocean by the decomposition of organic matter.

These sources of fluctuation are definitely correlated with the elevation and extension of the land, on the one hand, and the extension of the sea and the reduction of the land, on the other. During an extensive elevation of the land, silicates are converted into carbonates at an increased rate and the limestones and dolomites are dissolved and carried to the sea more rapidly, both processes involving an acceleration of the consumption of carbon dioxide. Correlated with this extension of the land is a reduction of the sea area attended especially by a lessening of the area of the continental shelves which are the habitat of the chief lime-secreting life, while the area available for pelagic surface life is also lessened. Reduction in the lime-secreting life retards the incidental process of freeing carbonic acid and returning it to the atmosphere. The result is a reduction of temperature which in turn increases the ability of the ocean to absorb carbon dioxide and reduces the dissociation of the second equivalent of carbon dioxide, thus further reducing the returning process and increasing the capacity of the ocean to hold carbon dioxide notwithstanding the reduction of the partial pressure in the atmosphere. The reciprocating processes are thus temporarily affected in opposite directions so as to conjoin their results.

In periods of sea extension and of land reduction (base-level periods in particular), the habitat of shallow water lime-secreting life is concurrently extended, giving to the agencies that set carbon dioxide free accelerated activity, which is further aided by the consequent rising temperature which reduces the absorptive power of the ocean and increases dissociation. At the same time, the area of the land being diminished, a low consumption of carbon dioxide both in original decomposition of the silicates and in the solution of the limestones and dolomites obtains. Thus the reciprocating agencies again conjoin, but now to increase the carbon dioxide of the air.

These are the great and essential factors. They are modified by several subordinate agencies already mentioned, but the quantitative effect of these is thought to be quite insufficient to prevent very notable fluctuations in the atmospheric constitution. As a result, it is postulated that geological history has been accentuated by an alternation of climatic episodes embracing, on the one hand, periods of mild, equable, moist climate nearly uniform for the whole globe; and on the other, periods when there were extremes of aridity and precipitation, and of heat and cold; these last denoted by deposits of salt and gypsum, of subaërial conglomerates, of red sandstones and shales, of arkose deposits, and occasionally by glaciation in low latitudes.

T. C. CHAMBERLIN.

[The continuation of this article in the next number will embrace a discussion of the application of the hypothesis to known glacial periods, and to the oscillations from glacial to interglacial epochs, together with the agencies of localization, and a suggestion regarding the superposed minor oscillations.]